Stress Corrosion Cracking
of
HVOF Coated and Cr Plated AerMet 100 Steel

E. U. Lee, H. C. Sanders and S. Hartle
Naval Air Warfare Center Aircraft Division
Patuxent River, MD 20670

INTRODUCTION

The stress corrosion cracking (SCC) behavior of HVOF coated and Cr plated AerMet 100 steel was studied at Naval Air Warfare Center Aircraft Division, Patuxent River, MD. The result is presented in this paper.

EXPERIMENTAL PROCEDURE

Base Metal

As the base metal, a forged slab of AerMet 100 steel, 1 inch thick, was used. Its chemical composition, heat treatment and mechanical properties are as follows.

- Chemical Composition (wt %)
  C: 0.23, Cr: 3.1, Ni: 11.1, Mo: 1.2, Co: 13.4, Fe: Balance
- Heat Treatment
  - Solution Treatment at 885^{o}C for 75 Minutes in Argon and Cooling in Nitrogen
  - Freezing in Dry-Ice and Alcohol
  - Aging at 482^{o}C for 5 Hours in Air
- Mechanical Properties
  - Yield Strength (ksi): 250
  - Ultimate Tensile Strength (ksi): 285 – 300
  - Elongation (%): 14
  - K_{IC}: (ksi√in) 115

Specimen

A buttonhead round rod specimen [1], Figure 1, was selected for the primary SCC test. It was machined to have the longitudinal axis parallel to the rolling direction of the AerMet 100 steel slab. One group of specimens was bare. The second group was coated with 83% WC and 17% Co powders by means of HVOF thermal spraying at Engelhard Corp., East Windsor, Connecticut. The third group was Cr electroplated and baked at 375^{o}F for 24 hours in vacuum at NADEP Cherry Point with Mr. R. Kestler's help.

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A square bar specimen with a semi-circular edge notch, Figure 2, was used for the secondary SCC test. It was machined to have L-T crack plane orientation and HVOF coated with 83% WC and 17% Co powders.

Prior to the HVOF coating and Cr plating, the specimen surface was shot peened. The thickness of the coating and plating was 3 mil.

Residual Stress Measurement

Thermal spraying and electroplating have been known to induce residual stress, which influences the SCC behavior of the base metal. Therefore, the residual stress in the base metal was measured by X-ray diffraction after removing the HVOF coating and Cr plating by electropolishing.

SCC Test

The SCC resistance was determined, employing an accelerated test method of rising step load[2], in 3.5% NaCl solution of pH 7.3. The test machine included 2 loading devices for sustained tension and 4-point bending, 2 environmental chambers, 2 pumps for circulation of salt solution, and 2 potentiostats, as shown in Figure 3. During the test, the specimen was the working electrode in a 3-electrode cell with a saturated calomel reference electrode and a platinum counter-electrode. Cathodic potentials, ranging from -1.2 volt to the open circuit potential, were applied to generate various amounts of hydrogen at the specimen. The open circuit potentials were –0.52 volt for the bare specimen, and –0.42 volt for the HVOF coated and Cr plated specimens.

The threshold stress intensity factor for SCC, K_{ISCC}, can not be determined with a coated or plated specimen, which has no pre-crack. Therefore, in the primary SCC test, the threshold stress for SCC, σ_{ISCC}, was determined at various cathodic potentials with the buttonhead round rod specimen under sustained tension. In the secondary SCC test, the cracking and flaking of the HVOF coating, interface corrosion, and initiation and growth of stress corrosion crack were examined with the square bar specimen under sustained 4-point bending.

RESULTS AND DISCUSSION

Residual Stress

The residual stress in the base metal, beneath the HVOF coating and Cr plating, was found to be compressive and changing with depth, as shown in Figure 4. In the HVOF coated specimen, the compressive residual stress increases to the peak, -87 ksi, at depths, ranging from 1.6 to 3.9 mil, and then diminishes with increasing depth. Its layer is about 7.5 mil deep. In the Cr plated specimen, the peak compressive residual stress is –133 ksi at depth 1.5 mil, and its layer is about 4 mil deep. Compared to the HVOF coated specimen, the Cr plated one has a greater peak but a shallower layer of compressive residual stress.

McGrann[3] also reported similar features of compressive residual stress distribution in 83% WC/17% Co HVOF coated and Cr electroplated 4130 steel specimens. He observed the residual stress greater in the HVOF coated specimen than in the Cr plated one.

It has been shown that an intrinsic compressive residual stress is induced as the HVOF coating cools down to ambient temperature. Such a compressive residual stress can enhance the SCC and fatigue resistance. On the one hand, there is possible reduction of compressive residual stress and degradation in the strength of the heat-affected substrate (over tempering) due to the heat input involved in the HVOF process. Such reduction of compressive residual stress and degradation of strength would reduce the SCC and fatigue resistance. The magnitude of the SCC and fatigue resistance observed must reflect those effects. The Cr plating process, by contrast, will not affect heat treated substrates, since it is performed at temperatures near ambient. However, the Cr plating is associated with residual tensile stresses and accompanied by reduction of SCC and fatigue resistance. On the other hand, in this study, the specimens were shot peened before the HVOF coating and Cr plating process, and the measured residual stresses were compressive. The measured compressive residual stress lower in the HVOF coated specimen than in the Cr plated one is attributable to the heat input in the HVOF coating process. Therefore, it is conceivable that the HVOF coating would involve more reduction of SCC resistance, if the heat input of the process is increased.

SCC

The variation of threshold stress for SCC, σ_{ISCC}, with cathodic potential, V_{SCE}, is shown in Figure 5. At V_{SCE} = -1.2 volt, the σ_{ISCC} is lowest for all three groups of specimens. With increasing V_{SCE}, the σ_{ISCC} increases to the peak at V_{SCE} = -0.8 volt, and then decreases.

At the open circuit potentials, σ_{ISCC} = 250, 222 and 192 ksi for the bare, Cr plated and HVOF coated specimens, respectively. At a given V_{SCE}, the bare specimen has a greater σ_{ISCC} than the Cr plated and HVOF coated specimens. This indicates that Cr plating and HVOF coating reduce the SCC resistance of the base metal, AerMet steel, in 3.5% NaCl solution. Though the difference is small, the σ_{ISCC} of the Cr plated specimen is greater than that of the HVOF coated one. This must be associated with the greater compressive residual stress in the Cr plated specimen than in the HVOF coated one.

During the SCC test, the Cr plating and HVOF coating on the specimen were flaked, as shown in Figure 6. Figure 7 shows a cross-section of a Cr plated buttonhead round rod specimen, normal to the longitudinal axis, in the vicinity of a flake. The plating was cracked obliquely to its surface and flaked along its interface. Corrosion pits are visible on the interface of the base metal. They are potential sites for crack initiation. It is probable that the corrosion pits were formed by galvanic corrosion of the base metal in the presence of more noble Cr plating and 3.5% NaCl solution, which seeped into the interface through plating cracks and flakes. Furthermore, the galvanic corrosion is believed to accelerate the subsequent initiation and growth of a stress corrosion crack in the base metal. Figure 8 shows a cross-section of a HVOF coated buttonhead round rod specimen. Similar flaking of coating and corrosion pits on the interface of base metal are seen. Figure 9 shows a cross-section of a HVOF coated square bar specimen. Cracking and flaking of coating, and cracking from the corroded interface into the base metal are observable. The crack path is mostly intergranular, branching and deflecting, typical of SCC, as shown in Figure 10.

SUMMARY AND CONCLUSION

- The residual stress in the HVOF coated and Cr plated specimens is compressive near the interface. In the HVOF coated specimen, the compressive residual stress, reaches its peak –87 ksi at depths 1.6 – 3.9 mil, and decreases with increasing depth. In the Cr plated specimen, the peak compressive residual stress is –133 ksi at depth 1.5 mil.

- The threshold stresses for SCC, σ_{ISCC}, at the open circuit potentials are 250, 222, and 192 ksi for the bare, Cr-plated and HVOF-coated specimens, respectively.

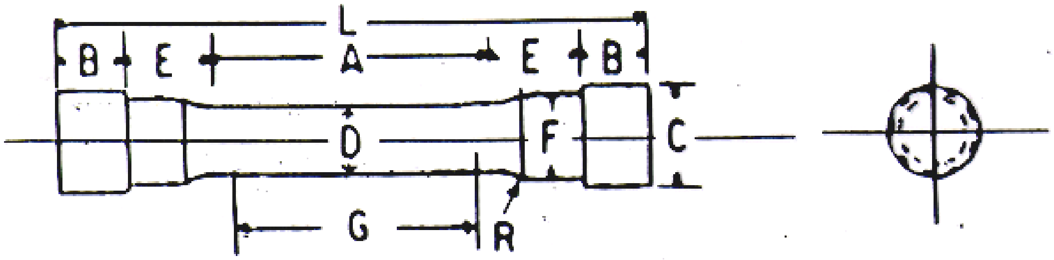
- The HVOF coating and Cr plating are flaked and cracked under sustained tension and 4-point bending in 3.5% NaCl solution.

- The SCC resistance is reduced by Cr plating and HVOF coating. This is attributed to the galvanic corrosion, which forms pits and accelerates the subsequent initiation and growth of stress corrosion crack, in the base metal.

- The Cr plated specimen has greater SCC resistance than the HVOF coated specimen. This is associated with its greater compressive residual stress.

REFERENCES

1. Metals Handbook, Vol. 8: Mechanical Testing, 9th ed. (Materials Park, OH: ASM International, 1985), p. 314.
2. Metals Handbook, Vol. 8: Mechanical Testing, 9th ed. (Materials Park, OH: ASM International, 1985), p. 539.
3. R. T. R. McGrann, J. R. Shadley, E. F. Rybicki, B. E, Bodger, W. A. Emery, D. A. Somerville and D. J. Greving< “Evaluation of Residual Stresses and Fatigue Life of Tungsten Carbide Thermal Spray Coated Aircraft Landing Gear Materials,” Proceedings of the 15th International Thermal Spray Conference, ITSC’98, Nice, France, May 18-22, 1998, pp. 557-562.



G - Gage length	= 1.000 +/- 0.005
D – Diameter (Note 1)	= 0.160 +/- 0.003
R – Radius of fillet, min	= 0.1562
A – Length of reduced section	= 1.250
L – Over-all length, approximate	= 3.000
B – Length of end section (Note 3)	= 0.160
C – Diameter of end section	= 0.280
E – Length of shoulder and fillet section, approximate	= 0.715
F – Diameter of shoulder	= 0.200

Figure 1. Buttonhead Round Rod Specimen

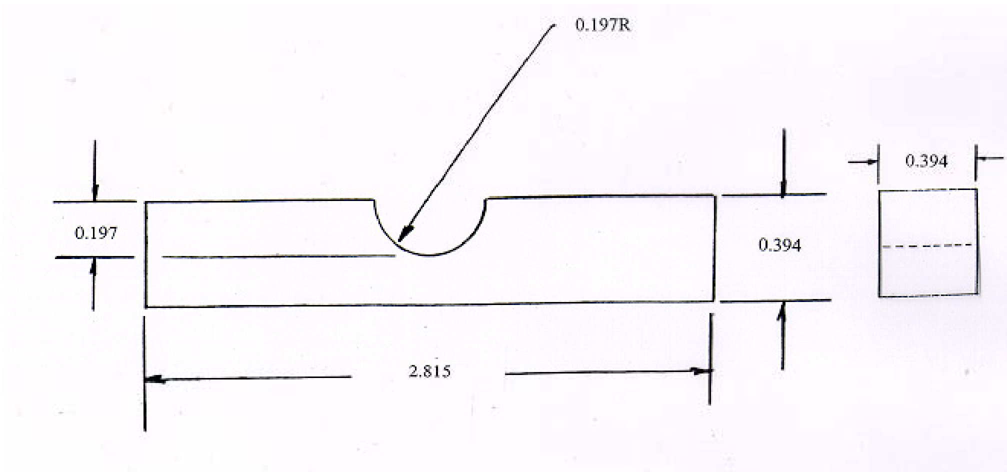


Figure 2. Square Bar Specimen with a Semi-Circular Edge North

Figure 3. Rising Step Load Test Machine

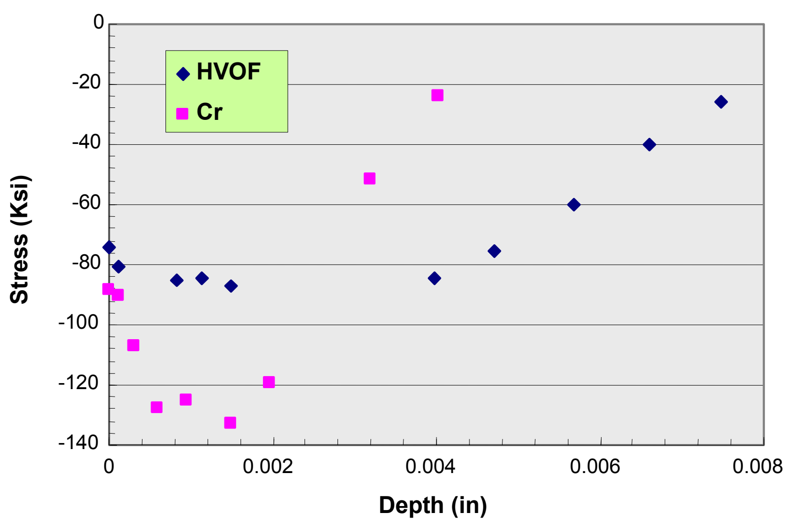


Figure 4. Profile of Residual Stress in Base Metal

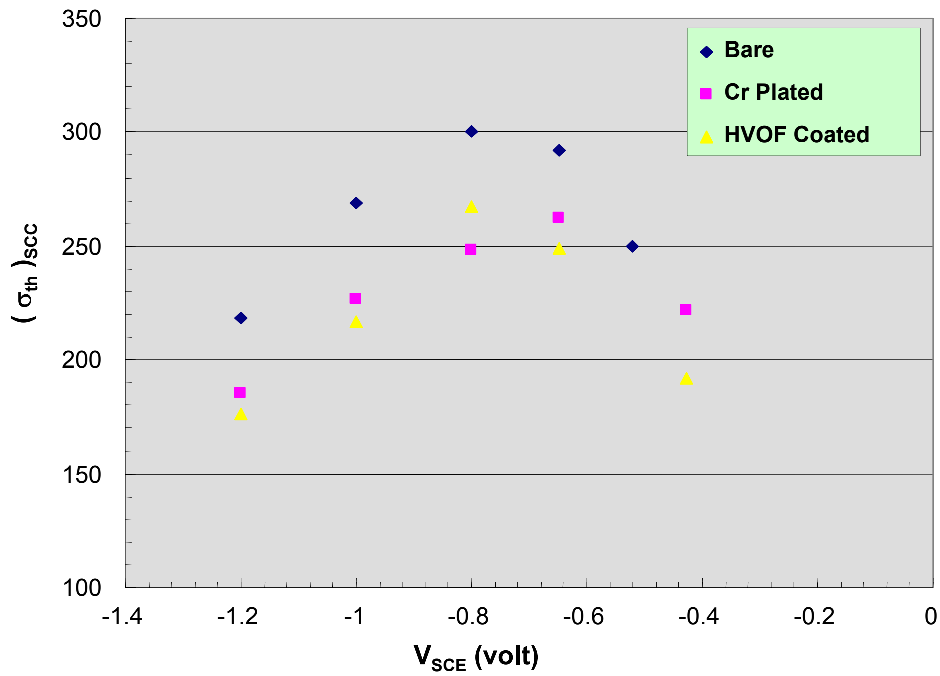
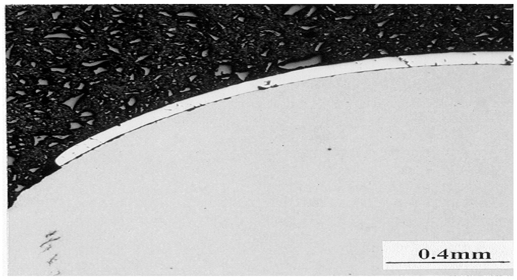


Figure 5. Variation of Threshold Stress for SCC, σ_{ISCC}, with Cathodic Potential, V_{SCE}

Figure 6(a) Flaking of Cr Plating during SCC Test

Figure 6(b) Flaking of HVOF Coating during SCC Test



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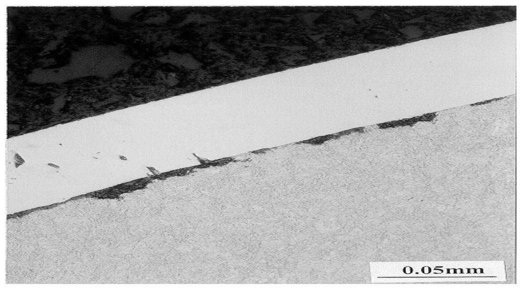

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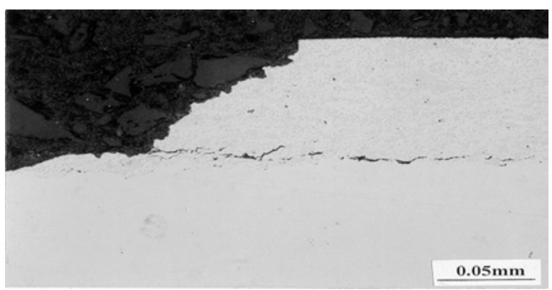
Figure 7. Cross-Section of Cr Plated Buttonhead Round Rod Specimen.



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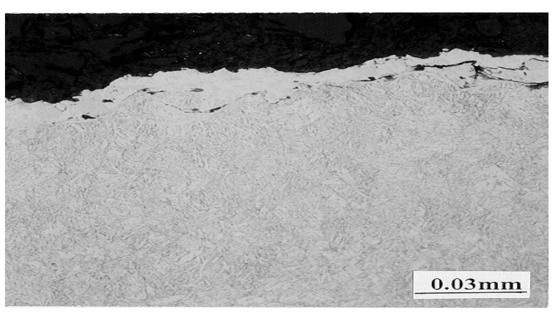

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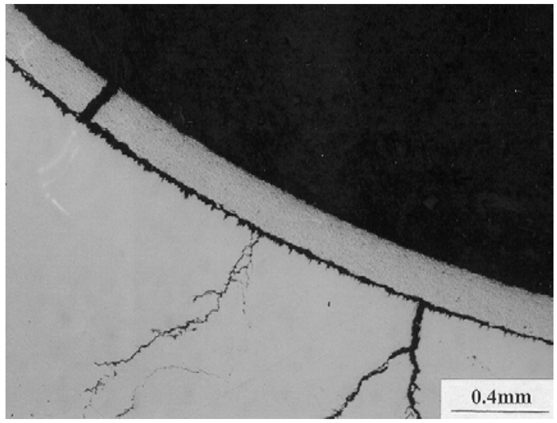
Figure 8. Cross-Section of HVOF Coated Buttonhead Round Rod Specimen.



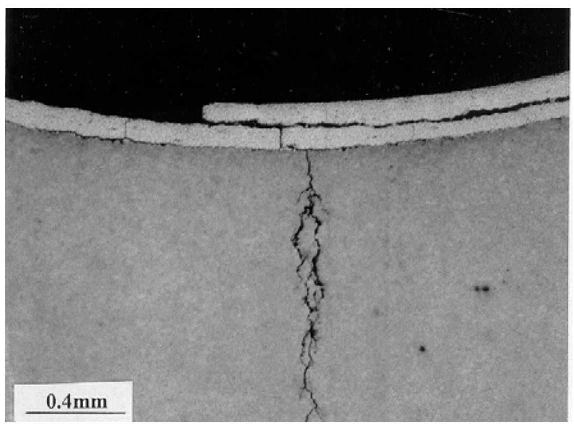


Figure 9. Cross-Section of HVOF Coated Square Bar Specimen

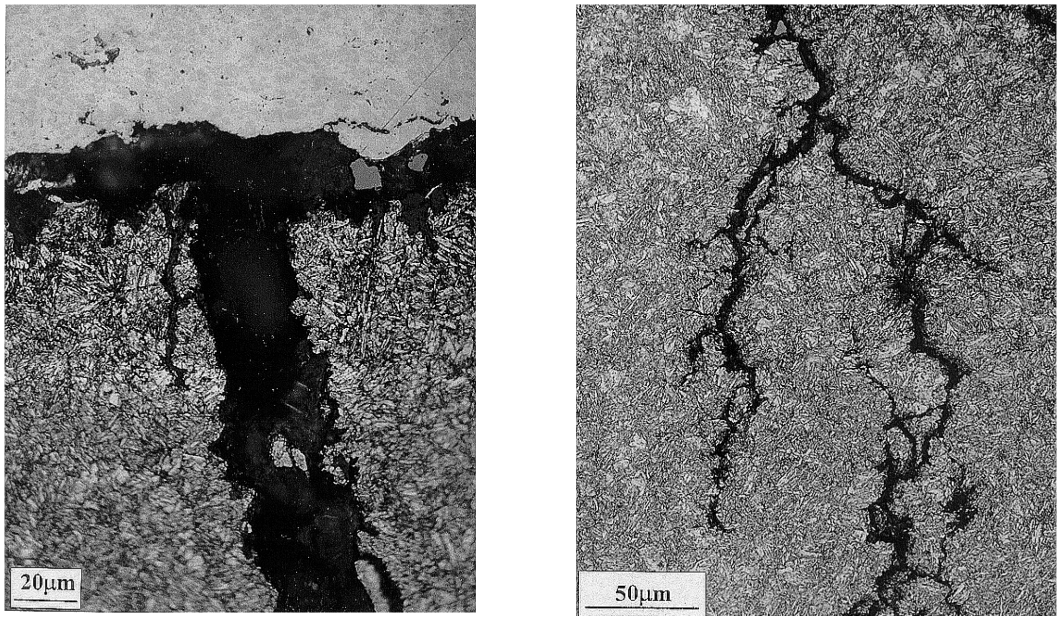


Figure 10. Crack Path in HVOF Coated Square Bar Specimen